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Effects of Service Environments on Aluminum- Brazed Titanium (ABTi)

W. L. Cotton

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Effects of Service Environments on Aluminum- Brazed Titanium (ABTi)

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Boeing Commercial Airplane Company
Seattle, Washington

Prepared for
Langley Research Center
under Contract NAS1-13681



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and Space Administration

Scientific and Technical
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EFFECTS OF SERVICE ENVIRONMENTS ON ALUMINUM-BRAZED TITANIUM (ABTi)

W. L. Cotton
Boeing Commercial Airplane Company

SUMMARY

Previous work on the DOT/SST follow-on program showed that the environmental corrosion resistance of aluminum-brazed titanium honeycomb sandwich was basically satisfactory. Short-term investigations indicated that titanium brazed with 3003 aluminum alloy was inherently resistant to corrosion under anticipated aircraft service conditions. Passivation films on both the aluminum and titanium surfaces effectively prevented galvanic coupling under the service environments evaluated. Chromate-inhibited primers provided additional corrosion protection for exposed panel edges.

The present program was designed to continue the long-term flight service and jet engine exhaust tests initiated under the original program and to perform additional tests to evaluate degradation of ABTi structure during prolonged exposure to extreme environments. The extreme service tests included elevated temperature exposure to fuels, lubricants, deicing-cleaning-and-stripping chemicals, and seawater, followed by accelerated laboratory corrosion tests. The evaluations were performed using solid-face and perforated-face honeycomb sandwich panel specimens, stressed panel assemblies, and faying-surface brazed joints.

The results of the investigation confirm the fact that the corrosion resistance of ABTi structure is satisfactory for commercial airline service. The unprotected ABTi system proved inherently resistant to attack by all of the extreme service aircraft environments except the following: seawater at 700 K (800° F) and above, dripping phosphate ester hydraulic fluid at 505 K (450° F), and a marine environment at ambient temperatures. The natural oxides and deposits present on titanium surfaces in normal aircraft service provide adequate protection against hot salt corrosion pitting. Coatings are required to protect titanium against dripping phosphate ester hydraulic fluid at elevated temperatures. Coatings are also required to protect acoustic honeycomb sandwich parts against corrosion when exposed to the weather in a marine environment.

INTRODUCTION

Aluminum-brazed titanium (ABTi) honeycomb sandwich is attractive for aircraft structural and acoustic applications, especially at service temperatures between 400 and 700 K (300° and 800° F). The corrosion resistance of the ABTi system during short and intermediate time exposure to a broad range of service environments was established by a program under the sponsorship of the Department of Transportation (DOT, report FAA-SS-73-5-6).

The purpose of the current NASA sponsored program was to perform additional tests to evaluate degradation of ABTi during extended exposure to extreme service environments. Flight service, jet engine exhaust exposure, and creep rupture tests initiated under the DOT contract were also continued, in order to provide 4- to 8-year environmental service data under the conditions encountered during actual usage. Extreme environment tests were conducted to determine the effects of flight service environmental fluids, temperatures, and stresses on ABTi structure during exposures of up to 7 months.

The overall scope of the DOT and NASA corrosion programs are shown in table 1.

All brazed honeycomb sandwich test parts were fabricated from Ti-6Al-4V titanium face sheets, Ti-3Al-2.5V titanium core, and 3003 aluminum braze alloy. Specimens were vacuum retort brazed per Boeing specification XBAC 5967 (see DOT report FAA-SS-73-5-8) by shop personnel under production conditions.

Because of significant differences in processing and corrosion parameters, four different types of parts are described in this report:

1. *Structural honeycomb* panels are all honeycomb sandwich panels which have solid face sheets.
2. *Acoustic honeycomb* panels are honeycomb sandwich panels which have one solid face sheet and one perforated face sheet. These panels are designed for noise attenuation applications.
3. *Faying-surface* panels have two solid face sheets directly brazed together.
4. *Open-face* specimens are titanium sheet, braze-coated on one surface with aluminum to obtain various aluminum to titanium exposed area ratios.

This report covers the results of the extreme service tests; phases II, III, and IV of the NASA program. The extended service evaluations, phase I, are still underway and are not treated in this report.

The use of commercial products or names of manufacturers in this report does not constitute official endorsement of such products or manufacturers, either expressed or implied, by the National Aeronautics and Space Administration.

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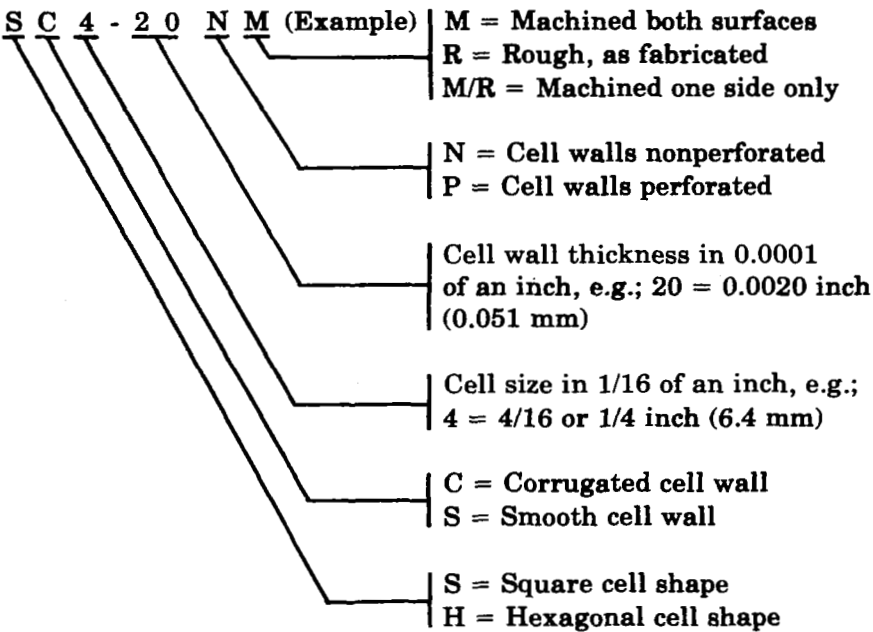


Table 1. — Corrosion Test Summary and Schedule

Test	Year									
	½	1	1½	2	3	4	5	6	7	8
Service evaluation										
Creep rupture	● ▲	●	● ▲	● ▲	○ ▲	○ ▲	● ▲	● ▲		
727 landing gear	● ■ ▲	● ■ ▲	● ■ ▲	● ■ ▲	○ ■ ▲	○ ■ ▲	○ ■ ▲	○ ■ ▲		●
737 flight spoilers	○ ▲	○ ▲		○ ▲	○ ▲	○ ▲				
YF-12A wing bay		●		○	○	○	●	●		
Jet engine exhaust	● ■	● ■	○ ■	○ ■	○ ■	○ ■	○ ■	○ ■		
Accelerated lab tests	Months									
	½	1	2	3	4	6	12	18		
Salt spray		▲ ● ■ ▲		▲ ● ■ ▲		▲ ● ■	● ■	●		
Alternate immersion		▲ ●	▲	▲ ●		▲ ●	●	●		
Acidified salt spray		▲	▲	▲		▲				
Tidal immersion		▲	▲ ● ■	▲		▲	● ■	●		
Stress corrosion		●	▲	▲	●	●	●	●		
Faying-surface joints		▲	▲	▲	▲	▲	▲			
Fundamental studies										
Solution potential	◆	◆								
Polarization	◆ ▲	◆ ▲								
Weight loss	◆	◆	◆		◆		◆			
Effect of pH	◆ ▲	◆ ▲		▲		▲				
Crevice mechanism	◆ ▲	◆ ▲	▲	▲	▲	▲	▲			
Extreme service tests	Days									
	4	7	30	60	90	120	180	210	390	
Thermal exposure	○ □	○ □							○ □	
Service fluids									○ □	
Coatings	○ □	○ □				○ □				
Phosphate lubricants	○ □									
Salt spray						○ □				
Humidity							○ □			
Alternate immersion							○ □			
Stress corrosion							○ □	○ □	○ □	

Solid figure = test completed during DOT contract
open figure = test completed during NASA contract

x = test in progress

● Structural honeycomb;

■ Acoustic honeycomb;

▲ Brazed faying-surface joint

● Open-faced brazen specimen

SHORT-TERM INTERACTION EFFECTS

The effects of a combination of high temperatures and simulated extreme service environments were evaluated to determine whether there was interaction that could seriously degrade the structural integrity or the corrosion resistance of ABTi. Figure 1 shows the test sequence; 5000-hour thermal exposure with periodic contamination, followed by corrosion testing and/or flatwise tensile testing.

TEST SPECIMENS

Acoustic honeycomb sandwich panels were fabricated using 2.54-cm (1.000-in.) thick SC4-20NM core and 0.51-mm (0.020-in.) thick face sheets, one of which was stagger perforated with 1.3-mm (0.050-in.) holes to produce 35% open area. After brazing, the panels were carefully bandsawed, without coolant, to produce 5.08- by 5.08- by 2.64-cm (2.0- by 2.0- by 1.04-in.) specimens suitable for environmental exposure and flatwise tensile testing.

Structural honeycomb sandwich panels were fabricated using 2.54-cm (1.000-in.) thick SC4-20NM core and 1.52-mm (0.060-in.) thick face sheets. The brazed panels were carefully bandsawed, without coolant, to produce 5.08- by 5.08- by 2.84-cm (2.0- by 2.0- by 1.12-in.) nonstressed specimens and 5.08- by 30.5- by 2.84-cm (2.0- by 12.0- by 1.12-in.) stress-corrosion specimens.

The stress-corrosion structural honeycomb specimens were assembled in pairs as shown in figure 2, using Ti-6Al-4V titanium bolts and silver-plated A286 corrosion-resistant steel nuts. Centered, double-tapered Ti-6Al-4V titanium shims were used to produce the fiber stresses shown in table 2 in the extreme titanium face sheets. The 5000-hours exposure at temperature was expected to result in approximately 15 MPa (2.4 ksi) relaxation in the outer fiber stress. Stresses in the braze alloy and core were not determined.

*Table 2. — Stress Corrosion Specimen Parameters**

Temperature (T)	505 K (450° F)	589 K (600° F)	700 K (800° F)	755 K (900° F)
Young's modulus (E) at temperature	9.72×10^{10} Pa (14.1×10^6 psi)	9.24×10^{10} Pa (13.4×10^6 psi)	8.27×10^{10} Pa (12.0×10^6 psi)	7.52×10^{10} Pa (10.9×10^6 psi)
Shim thickness (2y)	4.50 mm (0.177 in.)	2.51 mm (0.099 in.)	0.48 mm (0.019 in.)	0.30 mm (0.012 in.)
Applied stress (σ) at temperature	425 MPa (61.6 ksi)	226 MPa (32.8 ksi)	39 MPa (5.6 ksi)	22 MPa (3.2 ksi)
Calculated residual stress after 5000 hours at temperature*	415 MPa (60 ksi)	205 MPa (29 ksi)	30 MPa (4.2 ksi)	2.3 MPa (0.3 ksi)

*Assuming no yielding of the core or braze alloy

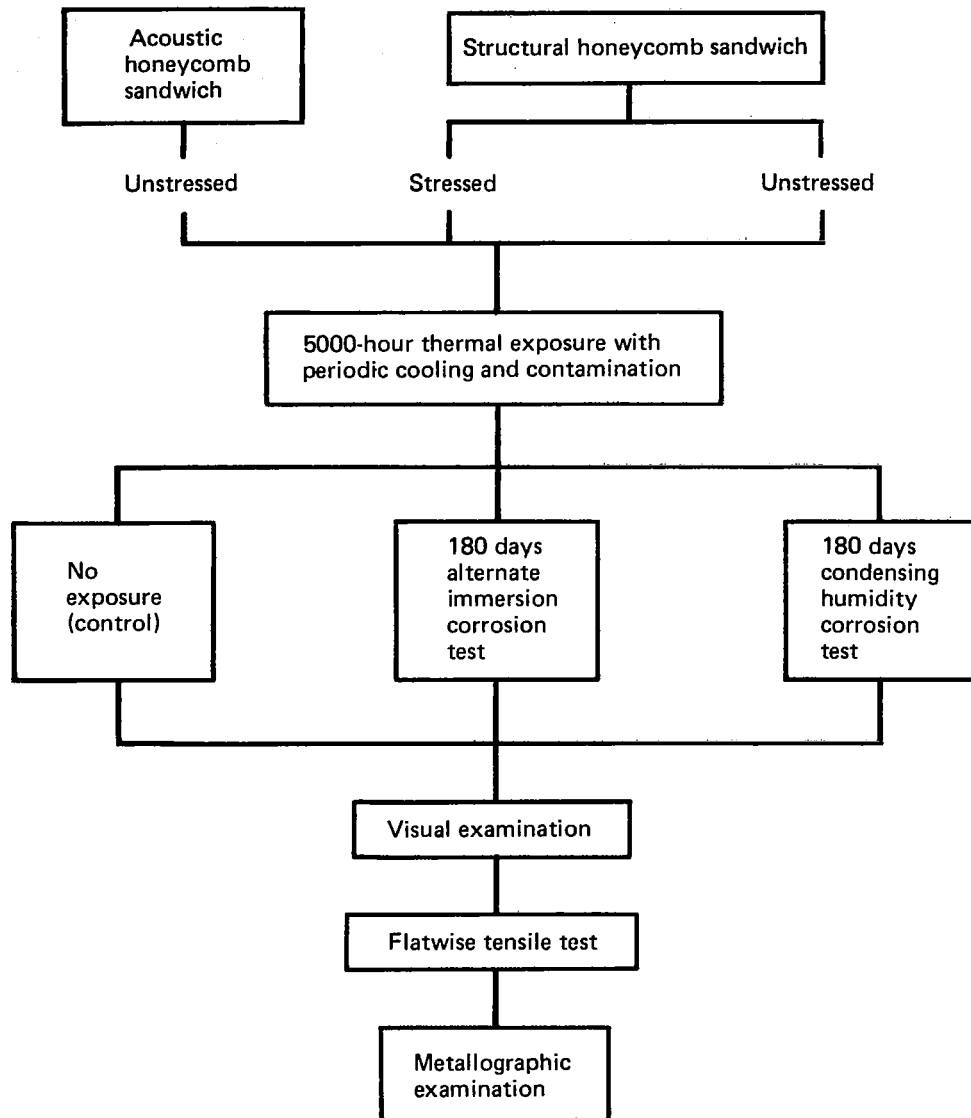


Figure 1. — Schematic Diagram of Test Sequence

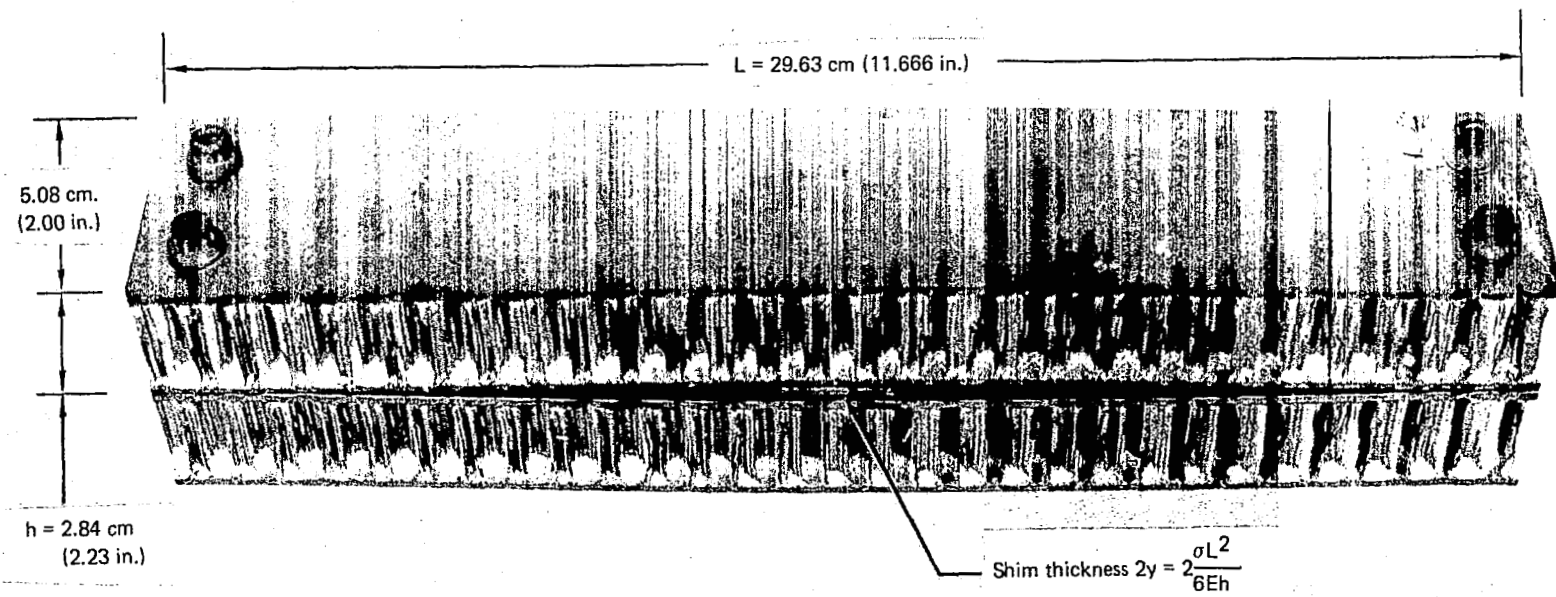


Figure 2. – Structural Honeycomb Stress Corrosion Specimens

TEST PROCEDURES AND SOLUTIONS

The test procedure (fig. 1) consisted of 5000-hour thermal exposure. The specimens were then separated into three equal groups for:

1. No further exposure
2. 180-day alternate immersion corrosion exposure
3. 180-day condensing humidity corrosion exposure

Specimen evaluation consisted of visual and metallurgical examination and flatwise tensile testing.

The thermal exposure was interrupted 30 times and a heavy, nonflowing coating of test fluid was sprayed onto all exposed surfaces of the specimens during cooldown. The test fluids, described in detail in table 3, were as follows:

1. Air (no test fluid)
2. A mixture consisting of 68 v/o engine fuel and lubricants, 23 v/o cleaning, stripping, and deicing materials, and 9 v/o synthetic seawater
3. Synthetic seawater alone

All thermal exposures were accomplished using electrically heated, forced air circulation furnaces. Furnaces were continuously controlled and monitored using independent thermocouples. Furnaces were currently certified for ± 1.1 K ($\pm 2^\circ$ F) instrumentation accuracy, and for ± 5.5 K ($\pm 10^\circ$ F) maximum difference between the control set temperature and any point within the furnace work zone.

Alternate immersion testing was accomplished per Federal Test Method Standard 151, method 823, by totally immersing the specimens for 10 minutes out of each hour in a neutral solution of 3.5% sodium chloride at 295 K (72° F). Test specimens were oriented so that the solution would have free access during immersion and, wherever possible, would concentrate at the test braze surface during drying. The test duration was 180 days.

Condensing humidity testing was accomplished per ASTM D-2247 at a temperature of 311 K (100° F). Specimens were oriented with the faces horizontal, perforated face up. The test duration was 180 days.

Table 3. — Synthetic Fluid Commercial Airline Service

Solution A - aircraft fuel and lubricants

Hydraulic fluid (MIL-H-5606)	33.3	V/O
Jet engine lubricant (MIL-L-7808)	33.3	V/O
Jet engine fuel (ASTM-D1655)	33.3	V/O

Solution B - cleaning, stripping, and deicing materials

Airplane deicing fluid (MIL-A-8243)	62	V/O
Runway deicing urea (MIL-U-10866)	16	g/l
Butyl Cellosolve (TT-T-776)	20	V/O
Methylene Chloride (MIL-M-6998)	10	V/O
Glacial Acetic Acid (O-A-76)	4	V/O
Wetting Agent (Triton X-100)	4	V/O

Solution C - Synthetic Seawater per ASTM D-1141

NaCl	24.54	g/l
MgCl ₂	5.20	g/l
Na ₂ SO ₄	4.09	g/l
CaCl ₂	1.16	g/l
KCl	0.69	g/l
NaHCO ₃	0.20	g/l
KBr	0.10	g/l
H ₃ BO ₃	0.30	g/l
SrCl ₂	0.02	g/l
NaF	0.003	g/l

Procedure

Add 100 ml of solution B and 40 ml of solution C to 300 ml of solution A. Shake or stir vigorously to provide maximum dispersion and agitate during application to minimize separation. Spray apply to deposit a continuous film and allow 10 minutes for evaporation of the volatile solvents prior to high - temperature burnoff.

Flatwise tensile testing was accomplished per MIL-STD-401 using 5.1- by 5.1-cm (2.0- by 2.0-in.) load blocks (fig. 3). In order to permit flatwise tensile testing, stress-corrosion beam specimens were carefully sawed, without coolant, into 5.08- by 5.08-cm (2.00- by 2.00-in.) segments having two environmentally exposed honeycomb edges; all other specimens had four environmentally exposed edges. Specimens were abrasively blast cleaned and bonded between the load blocks using Hysol EC-9628 adhesive at 395 K (250° F). Flatwise tensile tests were performed at room temperature at a crosshead speed of 1.3 mm/min (0.05 in/min).

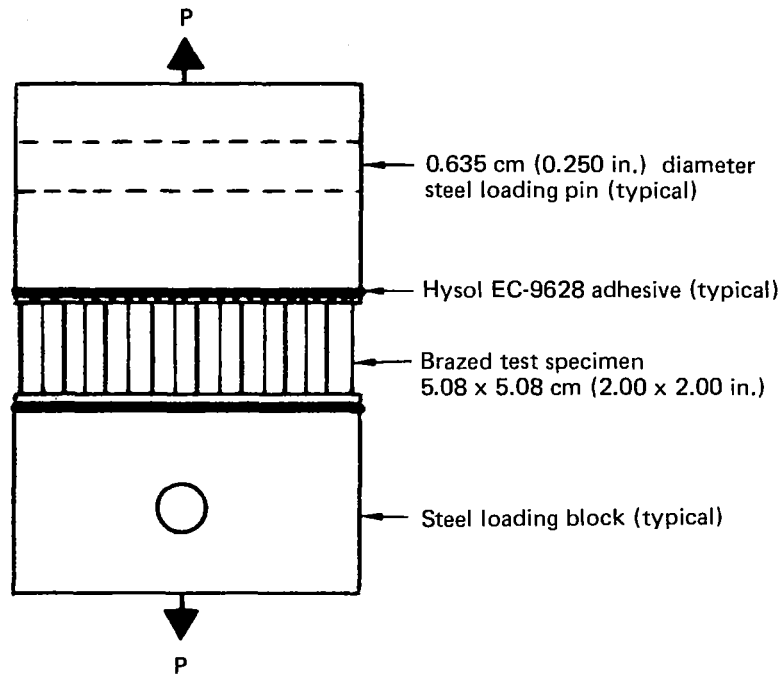


Figure 3. — Flatwise Tensile Test

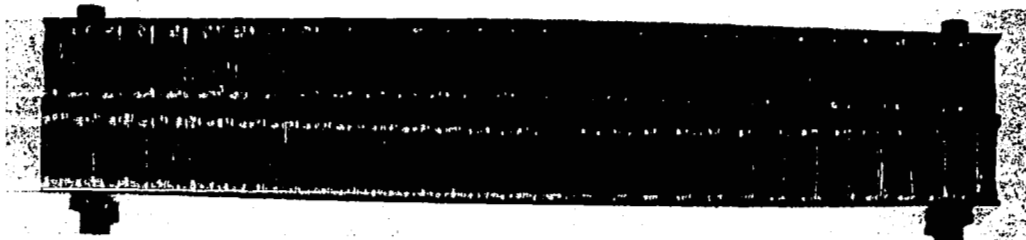
TEST RESULTS AND DISCUSSION (THERMAL EXPOSURE)

Figures 4, 5, and 6 show the appearance of ABTi honeycomb after 5000-hours exposure to various temperatures and fluids. Table 4 shows the effect of these exposures on flatwise tensile strength and on the hydrogen content of the exposed (outermost cell wall of acoustic) honeycomb core.

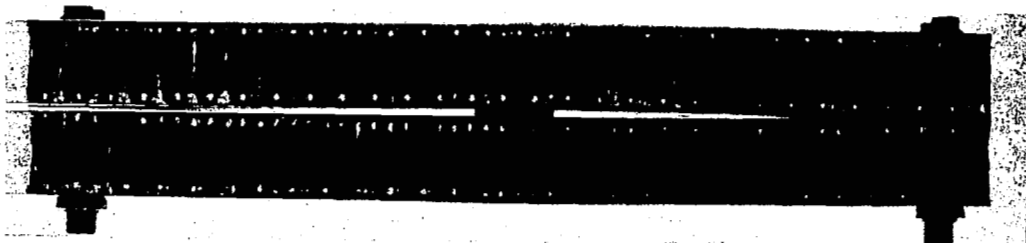
GENERAL OBSERVATIONS

Thermal exposure at 589 and 700 K (600° and 800° F) resulted in a slight increase in flatwise tensile strength. This phenomenon has been confirmed during other programs. The strengthening with prolonged artificial aging could be due to a combination of several phenomena: homogenization of the cast aluminum braze alloy, age hardening (fig. 7) of the aluminum by precipitation of finely dispersed Mn_3SiAl_{12} particles, and atomic diffusion to produce a $TiAl_3$ layer that becomes less brittle as the composition approaches stoichiometric perfection. Optical microscopy was not capable of resolving any discernible change in morphology or microstructure.

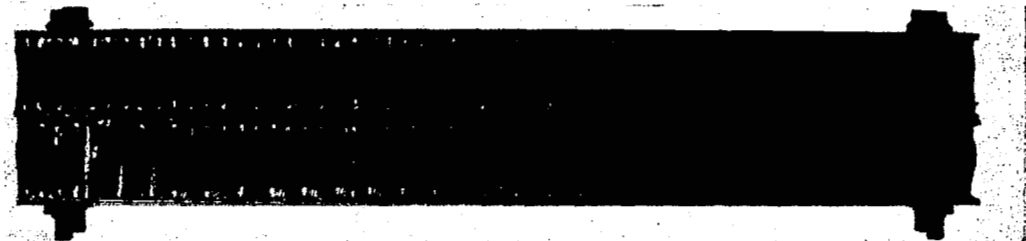
505 K (450° F)



589 K (600° F)



700 K (800° F)

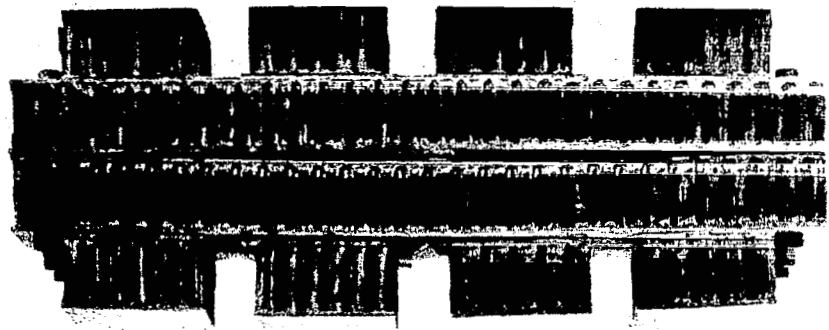


755 K (900° F)

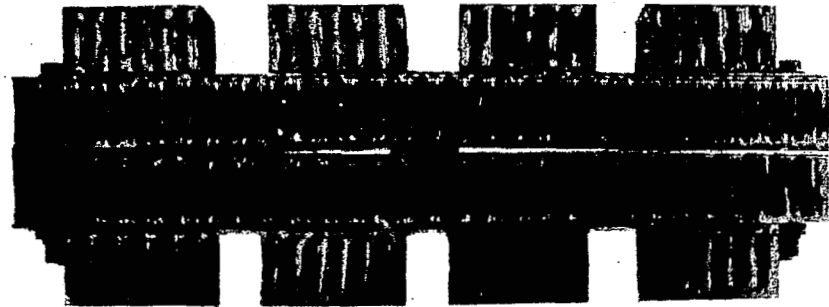


Figure 4. — 5000 Hours Thermal Exposure in Air

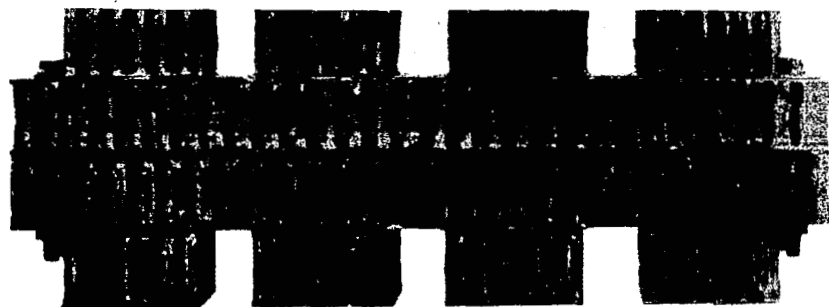
505 K (450° F)



589 K (600° F)



700 K (800° F)



755 K (900° F)

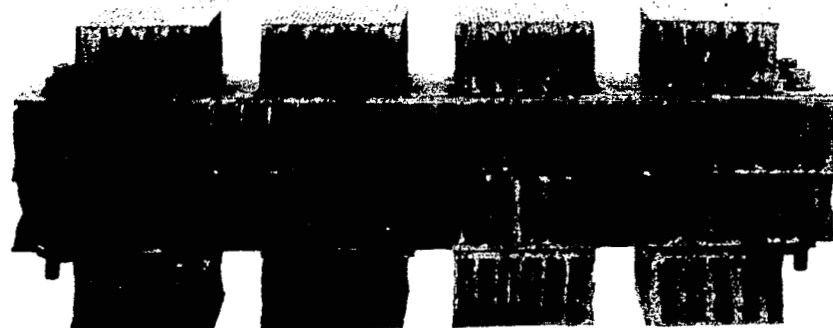
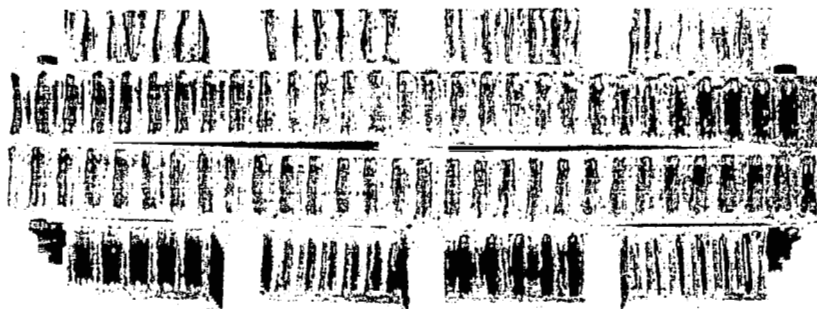


Figure 5. — 5000 Hours Exposure, Synthetic Airline Service Fluid

505 K (450° F)



589 K (600° F)



700 K (800° F)



755 K (900° F)



Figure 6. — 5000 Hours Exposure, Synthetic Seawater

Table 4. – Effect of Exposure on Strength and Hydrogen Content

Thermal exposure media	Type of specimen	Condition	Exposure temperature							
			505 K (450°F)		589 K (600°F)		700 K (800°F)		755 K (900°K)	
			FWT ratio ^a	H ₂ in core ^b (ppm)	FWT ratio ^a	H ₂ in core ^b (ppm)	FWT ratio ^a	H ₂ in core ^b (ppm)	FWT ratio ^a	H ₂ in core ^b (ppm)
Air	Structural	Stressed	0.92	132	1.06	109	1.16	85	0.11	161
		Unstressed	1.00		1.05		1.05		0	
	Acoustic	Unstressed	1.01		1.08		1.08		0.06	
Synthetic airline service	Structural	Stressed	0.99	155	1.11	85	1.12	159	0.08	284
		Unstressed	1.01		1.17		1.10		0.04	
	Acoustic	Unstressed	1.08		1.37		1.20		0.15	
Synthetic seawater	Structural	Stressed	1.03	136	1.08	132	1.03	760	0	880
		Unstressed	0.99		1.08		^c 0.76		0	
	Acoustic	Unstressed	0.94		1.29		^c 0.76		0.12	

^aRoom-temperature flatwise tensile strength ratio, average values: after exposure ÷ before exposure. Average FWT values before exposure: Structural specimens = 12.64 MPa (1834 psi); Acoustic specimens = 8.62 MPa (1250 psi).

^bHydrogen content of outer row of honeycomb core after exposure.

^cFailure occurred in the core, all other failures occurred in the braze.

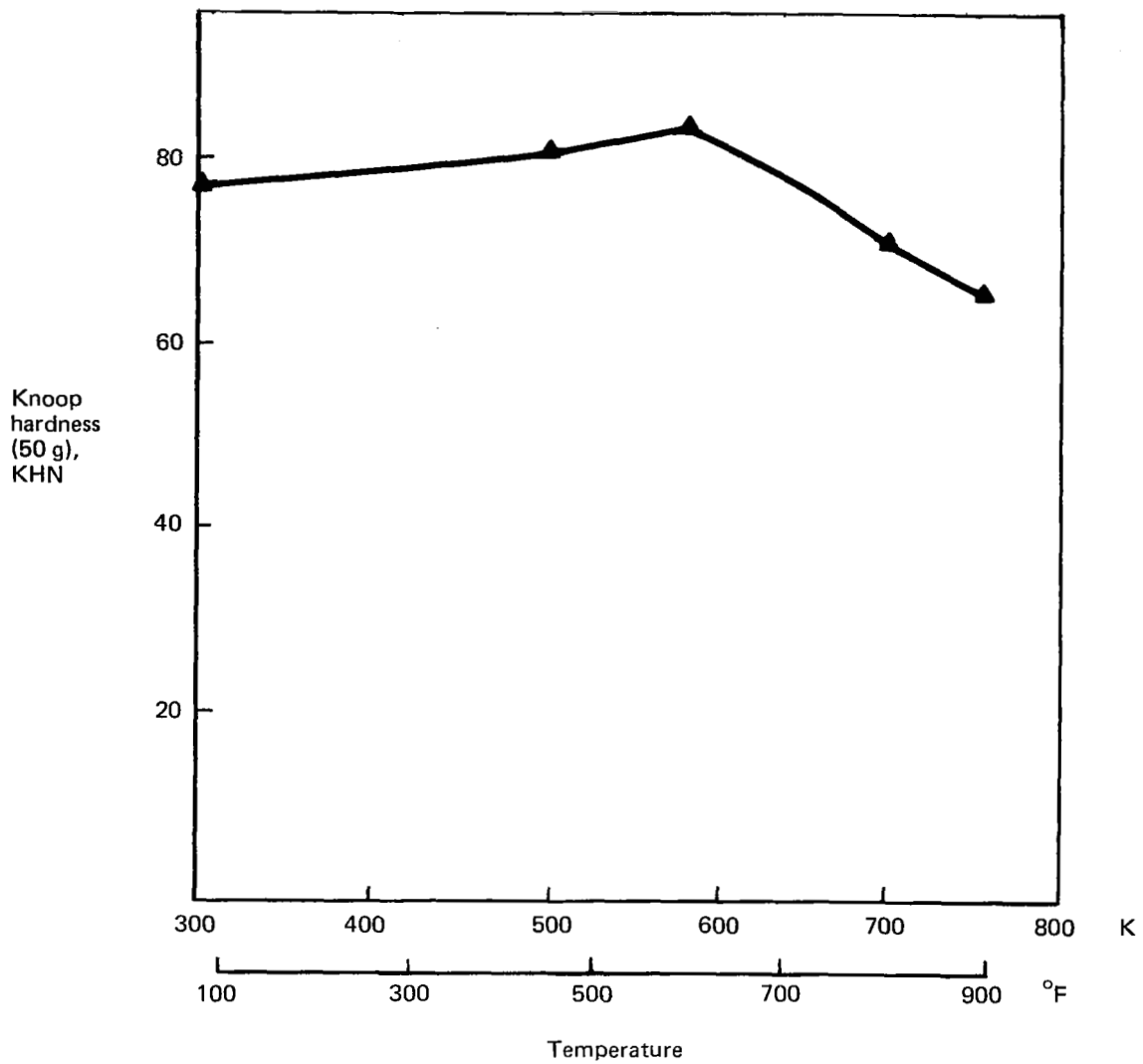


Figure 7. — Effect of 5000 Hours Aging on Hardness of Aluminum Braze Fillets

There was no evidence of stress corrosion or of cracking other than the hot-salt pitting that will be discussed in the section dealing with seawater exposure. The titanium face sheets that contacted silver-plated nuts did not show the liquid metal embrittlement that has been reported as sometimes occurring in jet engines. Exposure at 755 K (900° F) caused a reduction in the braze fillets and will be discussed separately.

AIR EXPOSURE

The 5000-hour thermal exposure in air resulted in an increasing oxide heat tint with temperature, as shown in figure 4. There were no signs of loose scale, structural oxidation damage, or hydrogen pickup.

SYNTHETIC AIRLINE SERVICE FLUID EXPOSURE

Thermal exposure coupled with periodic application of the synthetic service fluid resulted in the buildup of a heavy, reddish-brown deposit mainly consisting of nonvolatile residues from the lubricants and iron dissolved from the container for solution B. There was no loss of flatwise tensile strength at 700 K (800° F) and lower, and no evidence of pitting or galvanic attack of either the aluminum or the titanium. The increased hydrogen content after 5000-hours exposure at 755 K (900° F) resulted from the thermal dissociation of the seawater that contaminated the synthetic service fluid. Total hydrogen concentrations were much less than those caused by exposure to straight seawater because the reaction was partially suppressed by the lubricants in the synthetic service fluid. The hydrogen increase was not sufficient to seriously embrittle the thin titanium core and would have no effect whatever on the thicker titanium face sheets.

SEAWATER EXPOSURE

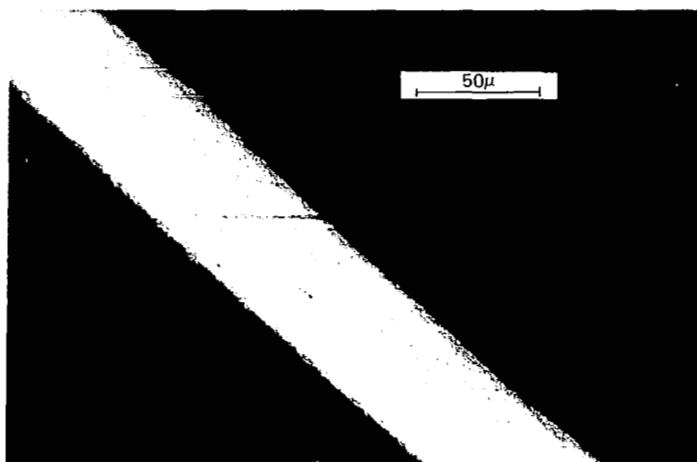
The 5000-hour thermal exposure coupled with periodic applications of synthetic seawater resulted in the buildup of a heavy layer of dried salts. There was a very discernible H₂S odor during spray application of the seawater to the hot specimens, indicating an appreciable thermal breakdown of the Na₂SO₄ constituent. There was no evidence of galvanic attack or corrosion pitting of aluminum at any temperature, indicating that the braze alloy is not susceptible to hot-salt corrosion at service temperature and that the 2-hour maximum exposure to aqueous salts during each application was insufficient to initiate the conventional corrosion mechanism.

Exposure to seawater at 700 and 755 K (800° and 900° F) resulted in extensive hydrogen pickup by the titanium core and a significant reduction in flatwise tensile strength, with all failures occurring in the titanium honeycomb core. The loss in flatwise tensile strength proved to be due to hot-salt pitting corrosion of the titanium core (see fig. 8). In the presence of stress, the occurrence frequently included planar cracks perpendicular to the direction of stress. At 755 K (900° F), pitting occurred at bare titanium areas and at the root of cracks through the aluminide layer (fig. 9). Hot-salt corrosion of titanium has been encountered previously, and is accompanied by

Note: During 5000-hour seawater exposure
Dilute Keller's Etch

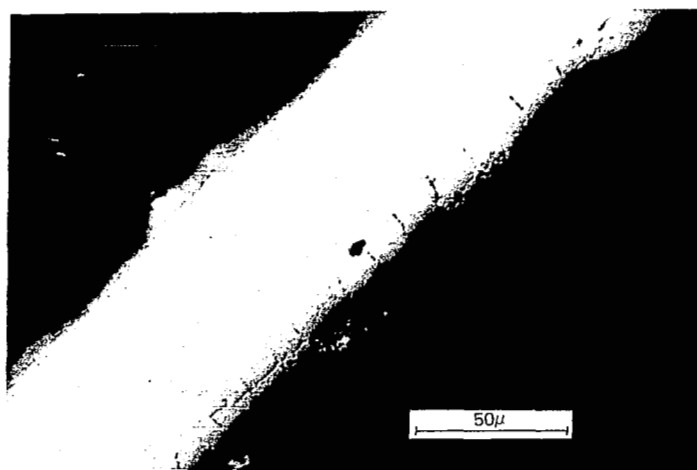
589 K (600° F)

No attack on
cell walls



700 K (800° F)

Shallow planar cracks
in cell walls



755 K (900° F)

Deep pits and cracks
in cell walls

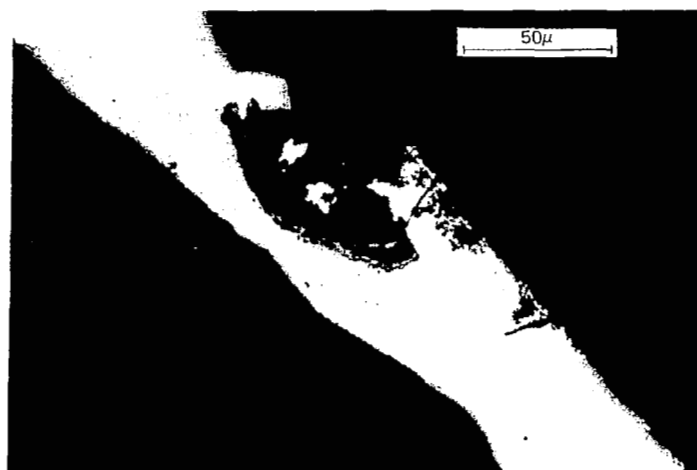
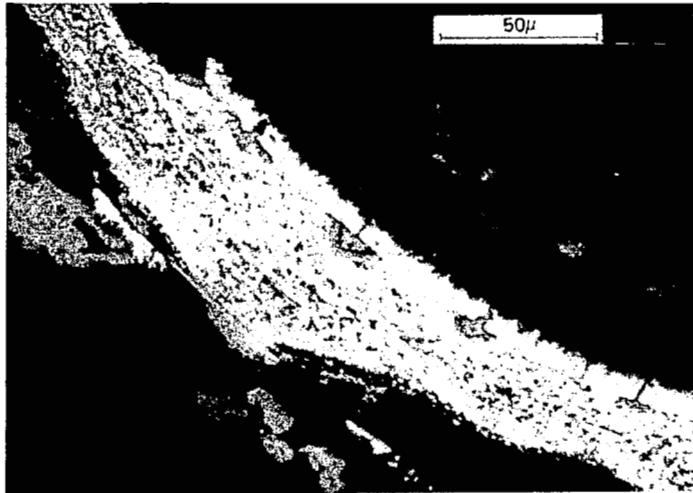


Figure 8. — Hot Salt Corrosion of Titanium Core

Note: During 5000-hour seawater exposure at 755 K (900° F)

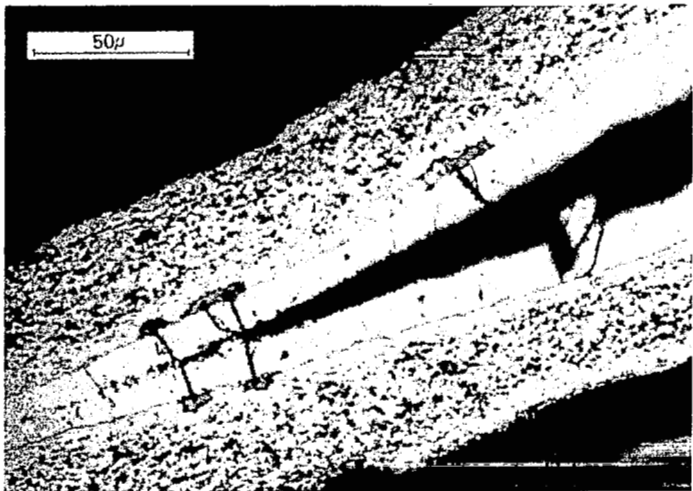
Cross section of core wall

Keller's Etch



Cross section of core node

Keller's Etch



Fillet area

Dilute Keller's Etch

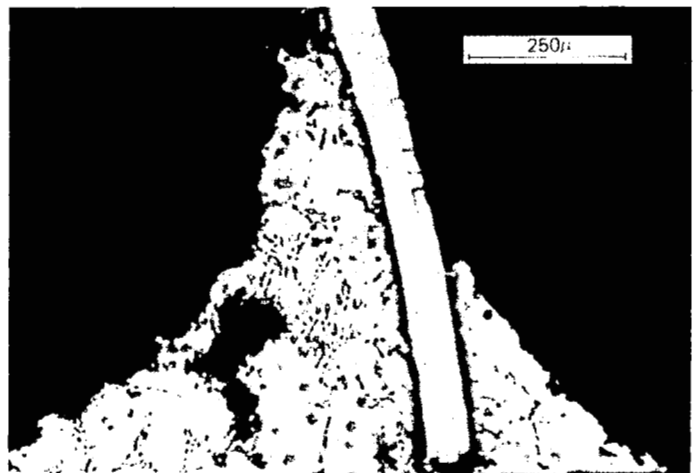


Figure 9. — Hot Salt Corrosion Penetration Through Aluminide Layer

hydrogen production (report NASA TN-D6779). The hot-salt corrosion mechanism has been shown (reports NASA TM X-68015 and NASA TM X-3145) to be stopped by cooling and not to be cumulative. The particular cooling frequency used in these tests, approximately once a week, magnified the degree of hot-salt pitting. The frequent cooldowns encountered in aircraft engines almost totally eliminate this attack, and there have not been any service problems with titanium engine components that could be attributed to hot-salt corrosion. It should be noted that this attack was inhibited or stopped almost completely when the seawater was mixed with the engine fuel, lubricants, and other components in the synthetic airline service fluid.

EXCESSIVE THERMAL EXPOSURE

Exposure for 5000 hours at 755 K (900° F) in each of the service media resulted in the disappearance of many of the aluminum braze fillets. Oxygen discoloration was evident in even the innermost cells of the structural honeycomb sandwich specimens. This degradation in properties was caused by solid-state conversion of the aluminum braze alloy to TiAl_3 . The controlling event occurring during brazing is the conversion of aluminum and titanium to titanium aluminide: $\text{Ti} + 3\text{Al} \rightarrow \text{TiAl}_3$. The growth of the TiAl_3 layer continues by solid-state diffusion at temperatures below the melting point of the aluminum braze metal. The TiAl_3 growth occurs by progressive thickening of the original aluminide layer at the expense of the adjacent aluminum (see fig. 10). The 5000-hour exposure at 755 K (900° F) was sufficient to consume all of the surface aluminum and most of the braze fillets, greatly lowering the flatwise tensile strength and permitting oxygen to penetrate into the interior of the structural honeycomb specimens. Figure 11 is a composite of data from various Boeing test programs showing the onset of solid-state TiAl_3 formation as a function of time and temperature. From this curve and from figure 10, it can be seen that the rate of TiAl_3 growth is very slow and would fulfill any expected aircraft life requirements at temperatures up to 700 K (800° F). Above 700 K (800° F), the life expectancy decreases rapidly with progressively higher temperatures. However, the system is shown to be capable of withstanding some exposure to temperatures approaching the melting point of the braze alloy, 2 hours at 920 K (1200° F), such as might be encountered in an engine fire.

TEST RESULTS AND DISCUSSION (SUBSEQUENT ENVIRONMENTAL TESTING)

Table 5 shows the synergistic effects of various environments on corrosion resistance as a function of flatwise tensile strength.

SPECIMEN SENSITIVITY

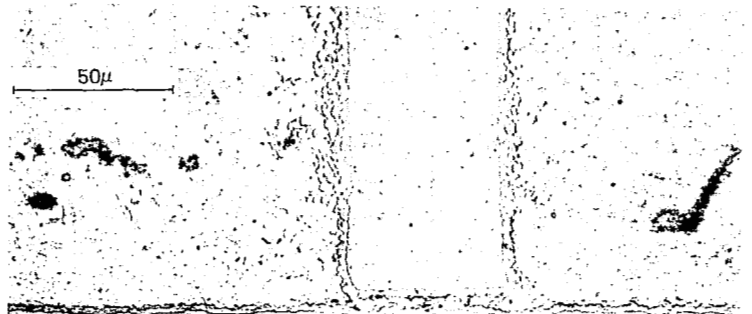
The stress concentrations and failure mode of flatwise tensile specimens made them especially sensitive to any damage to the outer braze fillet. Reduction in flatwise tensile strength served as an excellent test for the onset of corrosion damage by greatly magnifying the effects of damage. Reduction in flatwise tensile strength data must not be used to assess corrosion damage to actual structure. The percent of damaged fillets in flatwise tensile specimens will be many times that of actual structure, and actual honeycomb structure is rarely critically stressed in flatwise tension.

Note: During 5000-hour
thermal exposure
Dilute Keller's Etch

589 K (600° F)
 $\text{TiAl}_3 = 0.0013 \text{ mm}$
(0.00005 in.)



700 K (800° F)
 $\text{TiAl}_3 = 0.003 \text{ mm}$
(0.0001 in.)



755 K (900° F)
 $\text{TiAl}_3 = 0.03 \text{ mm}$
(0.001 in.)



Figure 10. — Growth of Aluminide Layer

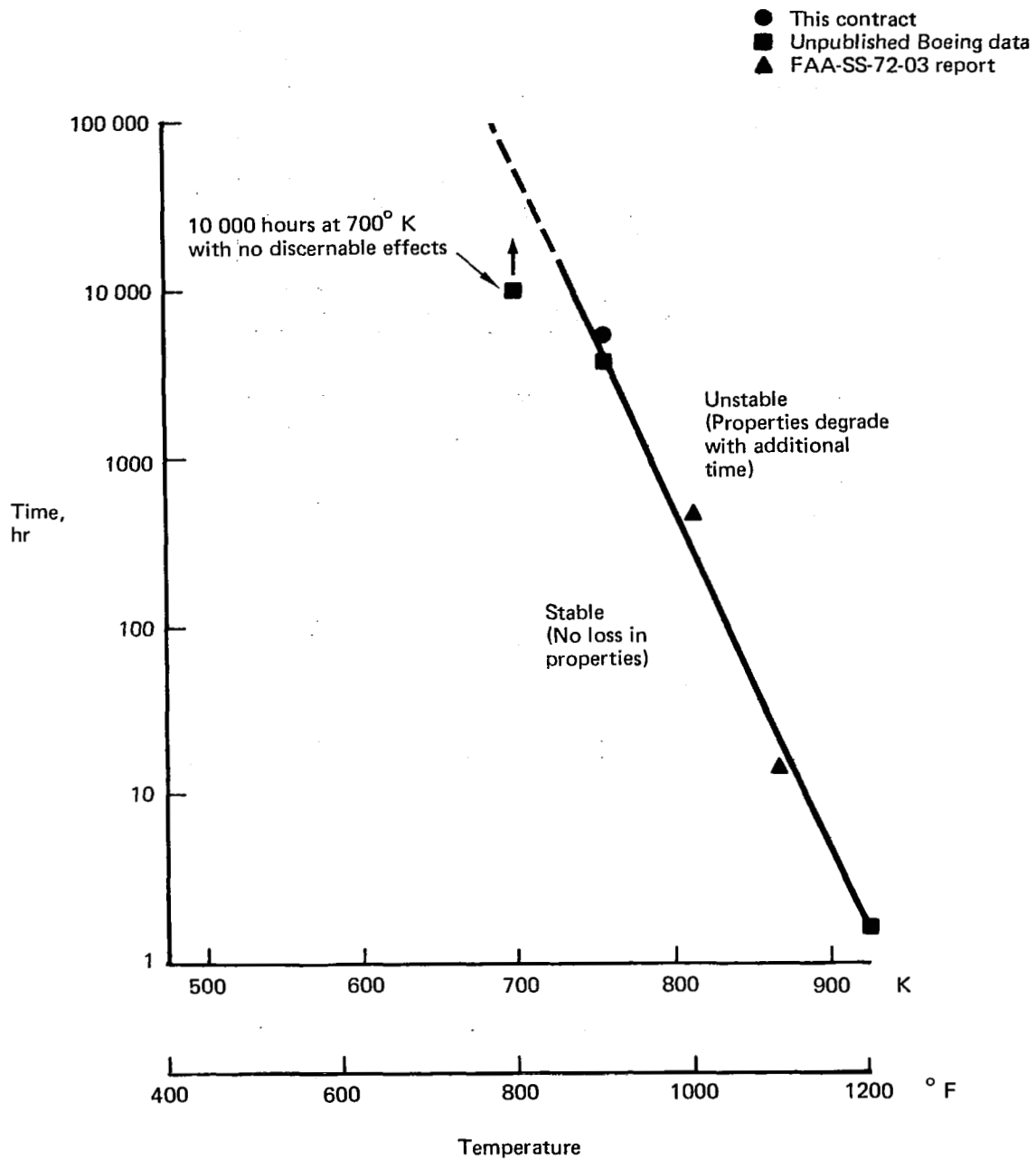


Figure 11. — Metallurgical Stability of ABTi

Table 5. — Effect of Service Exposure and Environmental Testing on Strength

Thermal exposure media	Type of specimen	Condition	Flatwise tensile strength ratio ^a after 5000 hours thermal exposure							
			505 K (450°F)		589 K (600°F)		700 K (800°F)		755 K (900°F)	
			Condensing humidity test	Alternate immersion test	Condensing humidity test	Alternate immersion test	Condensing humidity test	Alternate immersion test	Condensing humidity test	Alternate immersion test
Air	Structural	Stressed	0.89	0.42	1.05	0.52	1.09	0.55	0.05	0
		Unstressed	0.85	0.36	1.05	0.44	0.93	0.25	0.05	0
Synthetic airline service fluid	Acoustic	Unstressed	0.46	0	0.36	0	0.44	0	0	0
		Unstressed	0.46	0	0.36	0	0.44	0	0	0
	Structural	Stressed	0.58	0.27	0.82	0.54	0.90	0.46	0.05	0
		Unstressed	0.42	0.11	0.74	0.22	0.50	0.17	0.05	0
Synthetic seawater	Acoustic	Unstressed	0.17	0	0.28	0	0.18	0	0	0
		Unstressed	0.17	0	0.28	0	0.18	0	0	0
	Structural	Stressed	0.62	Not tested	Not tested	0.59	0.54	Not tested	Not tested	0
		Unstressed	0.80	Not tested	Not tested	0.28	0.53	Not tested	Not tested	0.05
	Acoustic	Unstressed	0.18			0	0.18			0
		Unstressed	0.18			0	0.18			0

^aRoom-temperature flatwise tensile strength ratio, average values: after exposure ÷ before exposure. Average FWT values before exposure: structural specimens = 12.64 MPa (1834 psi); acoustic specimens = 8.62 MPa (1250 psi).

Interpretation and analysis of the flatwise tensile results require consideration of the specimen geometry during the corrosion test. Corrosion of the peripheral fillets tended to disproportionately lower the apparent strength. In the case of the 5.08- by 5.08-cm (2- by 2-in.) unstressed structural honeycomb specimens, the outer directly exposed peripheral row of fillets amounts to approximately 40% of the total fillets in the specimens. In the case of the 5.08- by 30.5-cm (2- by 12-in.) stressed structural honeycomb specimens, the directly exposed peripheral fillets represent approximately 20% of the total fillets. Acoustic specimens, because of the perforated face sheet, have all fillets directly exposed to the corrosive media.

GENERAL OBSERVATIONS

The increased strength after 5000-hour thermal exposure at 589 and 700 K (600° and 800° F) was still apparent after corrosion testing. There was no indication that this strengthening was a surface effect or that it contributed to any corrosion mechanism.

There was no evidence of stress corrosion or of stress-accelerated corrosion during any of the exposures. Sufficient creep occurred during the 5000-hour thermal exposure that the specimens were essentially unstressed during the subsequent corrosion tests. Previous tests (report FAA-SS-73-5-5) indicated that there was no stress corrosion or stress-accelerated corrosion of ABTi panels that had not been thermally exposed.

EFFECTS OF THERMAL EXPOSURE

The thick, uniform oxide film that formed on the aluminum braze fillets during thermal exposure in air, especially at 589 K (600° F), provided increased corrosion protection to the braze fillets. This oxide film protection is similar to that provided by the chemical and anodic conversion coatings for aluminum. As with all aluminum structures, additional corrosion protection to the exposed aluminum should be provided by the use of supplemental protective coatings.

The specimens exposed for 5000 hours at 755 K (900° F) exhibited little or no resistance to corrosion. The thermally diminished aluminum braze fillets did not have sufficient continuity to prevent solution penetration, or sufficient thickness to resist 180 days of subsequent corrosion attack. This temperature is far beyond the design extended-service limit for the ABTi system. Any diminished braze fillets that would be caused by prolonged local overheating during service, would be readily detected by ultrasonic pulse-echo or eddy current inspection long before they become discontinuous.

CORROSIVENESS OF TEST MEDIA

Alternate immersion testing at room temperature proved to be a far more corrosive environment than 311 K (100° F) condensing humidity. The 50-minute drainage time during each alternate immersion cycle was insufficient to permit the recessed aluminum braze fillets to dry out and reform a protective oxide film, particularly in the interior of the acoustic specimens.

The corrosiveness of the alternate immersion and condensing humidity tests was increased by the deposits from the synthetic airline service fluid and the synthetic seawater. During alternate immersion testing, these deposits retained moisture and inhibited the drying portion of the cycle. During condensing humidity testing, the salt portion of the deposits ionized and accelerated the corrosiveness of the water, especially inside the cells of the acoustic honeycomb specimens.

ACOUSTIC HONEYCOMB

Corrosion of the acoustic specimens was more severe than that of the structural specimens. The large holes coupled with the 35% open area permitted free access to the corrosive test solutions and a high concentration of dissolved oxygen. Salts, leached from the synthetic fluid/thermal deposits, were effectively retained in the inner cells and caused extensive corrosion. The corrosion test results indicate that a thin-film coating should be used to protect interior surfaces of acoustic ABTi structure against corrosion, especially when the airplane is not in daily service and where the structure does not dry out in service.

SHORT-TERM EFFECTS OF COATINGS

The effect of coatings, designed to protect titanium from phosphate ester hydraulic fluids, on the corrosion resistance of acoustic ABTi sandwich was investigated. Figure 12 shows the coating tests and test sequence: tests to select the best of the candidate coatings, evaluation of the water leaching and corrosion resistance of the coatings, and thermal-phosphate ester fluid exposure and subsequent corrosion testing of coated acoustic honeycomb specimens.

TEST SPECIMENS AND PROCEDURES

COATING SELECTION

Specimens were 10- by 15- by 0.10-cm (4- by 6- by 0.040-in.) Ti-6Al-4V or commercially pure titanium. Surface preparation consisted of nitric-hydrofluoric acid etching, abrasive blasing with 150-mesh aluminum oxide, abrading with Scotchbrite type A fine aluminum oxide pads, or phosphate-fluoride conversion coating, depending on the coating supplier's recommendation or Boeing experience. Coatings were spray applied to the required thickness, air dried, and cured.

The dripping phosphate ester screening test was accomplished with the specimens mounted on a hot plate inclined at an angle of 0.79 radian (45°). Contact thermocouples and a recorder-controller were used to maintain the specimens at a temperature of 505.2 ± 5.6 K ($450 \pm 10^\circ$ F). The phosphate ester fluid, generally Skydrol 500B, was allowed to drip on the specimens at a rate of one drop approximately every 3 minutes for 96 hours. At the conclusion of the test, the charred deposits were removed with a solvent or a paint stripper and the specimens were examined for coating integrity and for etching or cracking of the titanium.

COATING PROPERTIES

Specimens for coating leaching studies were 5- by 5-cm (2- by 2-in.) Ti-6Al-4V or 3003-0 aluminum. The specimens were treated with two coats of monoaluminum phosphate (with and without a wetting agent) or with Kolene Kov Kote, and each coating was cured 10 minutes at 590 K (600° F).

The leaching test was accomplished by immersing each panel in a 250-ml beaker containing 200 ml of distilled water. Periodically, during exposure pH measurements were made. The beakers were tightly covered with 0.05-mm (0.002-in.) thick polyethylene during the 19-day exposure.

Specimens for salt spray testing of coatings were 10- by 15- by 0.02-cm (4- by 6- by 0.01-in.) 3003-0 aluminum. Specimens were alkaline cleaned and deoxidized (Amchem 6-16) for 2 minutes prior to Alodine 1200 treating and/or coating with monoaluminum phosphate or Kolene Kov Kote.

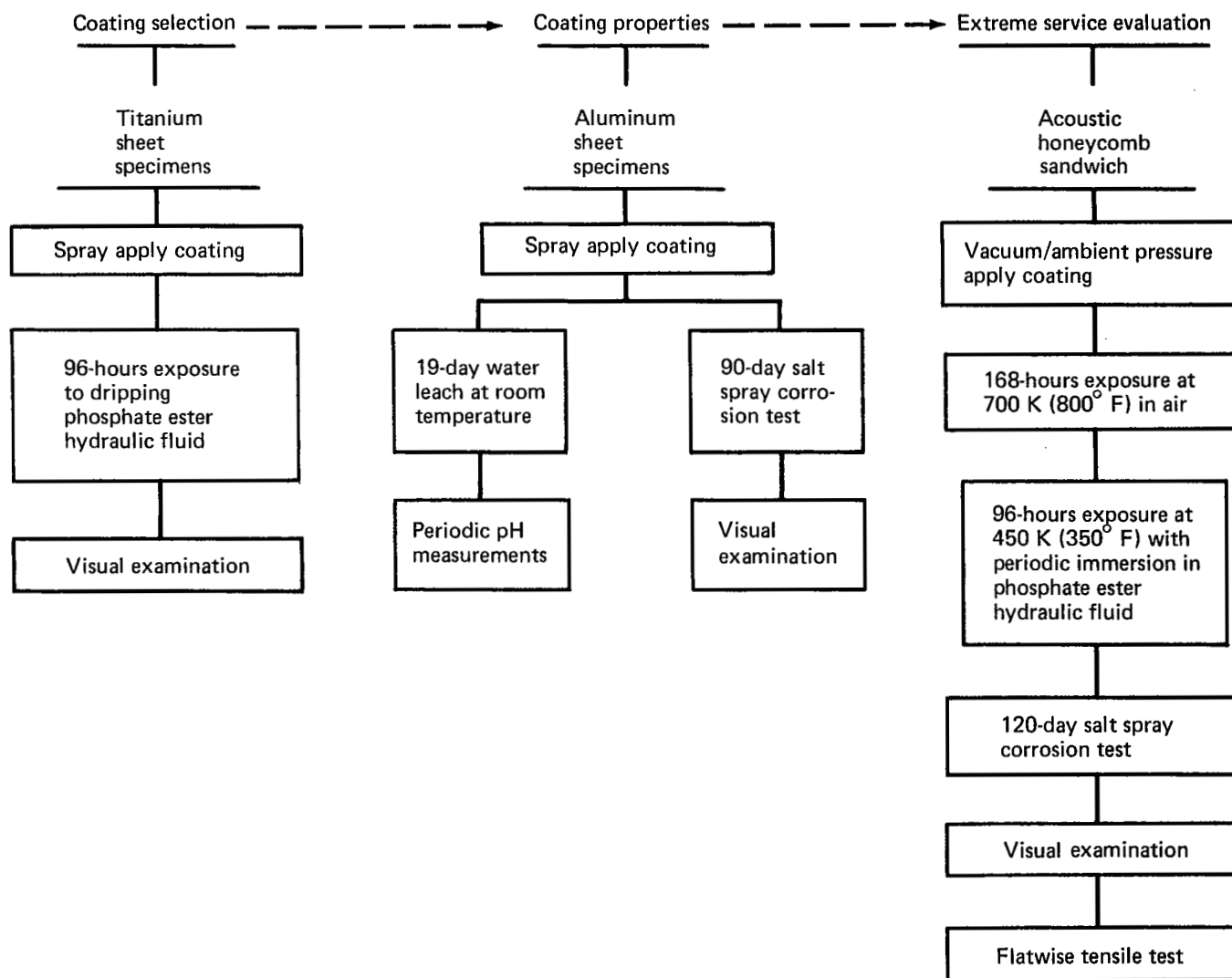


Figure 12. – Outline of Coating Tests

Salt spray testing was accomplished per specification ASTM B-117, using a 5% solution of neutral sodium chloride at 308 K (95° F). Test specimens were oriented so as to provide the most severe, uniform exposure of the aluminum to the salt fog. Sheet specimens for screening tests were inclined 0.105 radian (6°) from vertical. Acoustic honeycomb specimens were exposed in the horizontal position, with the perforated face sheet up to permit maximum exposure of the interior cells. Salt spray test exposures were for periods of 90 days for sheet specimens and 120 days for acoustic honeycomb sandwich specimens. Industry standard exposure periods for structural aluminum parts are: 14 days for parts protected with a specification MIL-C-5541 chemical coating, 21 days for parts protected with a specification MIL-A-8625 anodic coating, and 30 days for painted parts.

EXTREME SERVICE EVALUATION

Acoustic honeycomb sandwich specimens were fabricated as previously described, and the exposed honeycomb edges were abrasive blast-cleaned with aluminum oxide. The phosphate ester protection coatings (one coat of Andrew Brown B-2000 or two coats of Hanovia Gold no. 6854) were applied to the nonperforated face and cured. Secondary coatings to provide corrosion protection for the aluminum braze alloy (monoaluminum phosphate or Kolene Kov Kote) were applied by immersion vacuum/ambient pressure cycling three times. An Alodine 1200 pretreatment was not used prior to application of the second coating for two reasons: (1) the controls for the Alodine solution would require modification to accommodate the long immersion period during vacuum cycling, and (2) the need for an Alodine pretreatment had not been conclusively demonstrated.

The coated and cured acoustic honeycomb sandwich specimens were thermally exposed in a forced-air furnace at 700 K (800° F) for 168 hours. The temperature in the furnace was then lowered to 450 K (350° F) and thermal exposure was continued an additional 96 hours. The 450 K thermal exposure was interrupted nine times; the hot specimens were immersed in phosphate ester hydraulic fluid (Skydrol 500B) and returned to the furnace. The specimens were then cooled to room temperature and salt spray tested for 120 days.

TEST RESULTS AND DISCUSSION (COATINGS)

DRIPPING PHOSPHATE ESTER FLUID

Table 6 shows the results of the phosphate ester screening tests. Heavy, black deposits of fluid breakdown products formed on all of the specimens. Only two of the coatings (Andrew Brown B-2000 and Hanovia Gold no. 6854) proved capable of satisfactorily protecting titanium from the dripping fluid. The monoaluminum phosphate coating was porous, permitting the hydraulic fluid to spread laterally, retaining the corrosive fluid breakdown products, and generally aggravating etching of the titanium. The Kolene Kov Kote did not provide adequate protection against the dripping fluid when used alone. The Kov Kote did not degrade the performance of the gold coating and exhibited potential as a top coating to provide corrosion protection to assembled acoustic honeycomb parts.

Table 6. — Resistance of Coatings to Dripping Phosphate Ester Hydraulic Fluid

Coating designation	Titanium substrate	Surface preparation	Coating thickness, mm (inch)	Coating cure	Hydraulic fluid	Exposure at 505°K (450°F), hours	Results
None	CP	Alkaline cleaned	0.025 (0.001)	Baked at 535°K (500°F) for 30 minutes	Skydrol 500B	96	Substrate etched severely
Advanced Coatings 26W-1 (Fluoropolymer)	CP	HNO ₃ -HF etch	0.025 (0.001)	Baked at 535°K (500°F) for 30 minutes	Skydrol 500B	96	Coating removed; substrate etched severely
Advanced Coatings 26W-1 (Fluoropolymer)	CP	HNO ₃ -HF etch	0.025 (0.001)	Baked at 535°K (500°F) for 30 minutes	Hyjet IV	96	Coating removed; no damage to substrate
Advanced Coatings 26W-1 (old batch) (Fluoropolymer)	CP	Grit blasted	0.010 (0.0004)	Baked at 535°K (500°F) for 30 minutes	Skydrol 500B	96	Coating removed; substrate etched severely
Advanced Coatings 26W-1 (new batch) (Fluoropolymer)	CP	Grit blasted	0.010 (0.0004)	Baked at 535°K (500°F) for 30 minutes	Skydrol 500B	96	Coating removed; substrate etched severely
Hanovia Gold #6854	CP	HNO ₃ -HF etch	0.001 (0.00005)	Baked at 700°K (800°F) for 12 minutes	Skydrol 500B	96	Some coating removal; some substrate etching ppm H ₂ = 38
Hanovia Gold #6854	CP	HNO ₃ -HF etch; Scotchbrite abraded	0.001 (0.00005)	Baked at 715°K (825°F) for 15 minutes	Skydrol 500B	96	Some coating removal; some substrate etching ppm H ₂ = 30
Hanovia Gold #6854	CP	HNO ₃ -HF etch; Scotchbrite abraded	0.001 (0.00005)	Baked at 715°K (825°F) for 15 minutes	Aerosafe 2300W	96	Slight coating removal; no substrate etching ppm H ₂ = 33
Serma-Lon (Polyphenylene sulfide)	Ti-6Al-4V	Grit blasted	0.1-0.2 (0.005-0.010)	(Proprietary process)	Skydrol 500B	96	Coating removed; bad s substrate etching
Sermetal W (Aluminum + phosphate binder)	Ti-6Al-4V	Grit blasted	0.04-0.09 (0.0015-0.0035)	Baked at 605°K (625°F) for 30 minutes + glass bead peen	Skydrol 500B	96	Coating removed; substrate etched severely
Teflon-S 958-208 (Fluoropolymer)	Ti-6Al-4V	Non-grit blasted	0.025 (0.001)	Baked at 575°K (575°F) for 19 minutes	Skydrol 500B	96	Coating removed; bad substrate etching

Table 6. — (Concluded)

Coating designation	Titanium substrate	Surface preparation	Coating thickness, mm (inch)	Coating cure	Hydraulic fluid	Exposure at 505°K (450°F), hours	Results
Andrew Brown B-2000 (Silicate)	CP	PO ₄ -F1 treatment	0.041 (0.0016)	Dry 1 hour + bake at 450°K (350°F) for 1 hour	Skydrol 500B	96	Some coating removed; some substrate etching
Andrew Brown B-2000 (Silicate)	CP	PO ₄ -F1 treatment	0.041 (0.0016)	Dry 1 hour + bake at 450°K (350°F) for 1 hour	Hyjet IV	96	Some coating removed; no substrate etching
DeSoto Fluoropon (Fluoropolymer)	CP	Grit blasted	0.010 (0.0004)	Bake at 535°K (500°F) for 1 hour	---	Test not run	Coating softened at 500°K (440°F)
Dow Corning XR-62205 (Silicone)	CP	Grit blasted	0.025 (0.001)	Bake at 535°K (500°F) for 1 hour	Skydrol 500B	48	Coating removed; substrate etched severely
DeSoto 763-003 (Silicone)	CP	PO ₄ -F1 treatment	0.056 (0.0022)	Bake at 360°K (190°F) + 535°K (500°F) for 1 hour each	Skydrol 500B	96	Coating removed; substrate etched severely
Repaired panel 2 coats Hanovia Gold #6854	CP	HNO ₃ -HF etch	0.0002 (0.00001)	Bake at 700°K (800°F) for 12 minutes after each application	Skydrol 500B	96	No coating removed; no substrate damage
2 coats monoaluminum phosphate [70% Al(H ₂ PO ₄) ₃ + 10% MgNO ₃ + 20% CrO ₃]	CP	HNO ₃ -HF etch	0.08 (0.003)	Bake at 590°K (600°F) for 10 minutes	Skydrol 500B	96	Coating removed (a); substrate etched severely
2 coats Kolene Kov Kote	CP	HNO ₃ -HF etch	0.0008 (0.00003)	Bake at 590°K (600°F) for 10 minutes	Skydrol 500B	96	Coating removed (b); substrate etched severely
2 coats Hanovia Gold #6854 + 2 coats monoaluminum phosphate	CP	HNO ₃ -HF etch	0.08 (0.003)	Gold bakes + MAP bake ^a	Skydrol 500B	96	MAP coating removed (a); some gold removed; some severe etching
2 coats Hanovia Gold #6854 + 2 coats Kolene Kov Kote	CP	HNO ₃ -HF etch	0.001 (0.00004)	Gold bakes + Kov Kote bake	Skydrol 500B	96	Kov Kote removed (b); no substrate etching

^a2.5-cm (1-inch) wide band of MAP coating removed.^b0.8-cm (0.03-inch) wide band of Kov Kote removed.

The dripping phosphate ester fluid test simulates the most severe conditions that could be reasonably encountered in service. A slower drip permits corrosion fluid breakdown products such as phosphoric acid to evaporate. A faster drip rate flushes corrosive fluid breakdown products away. A lower temperature retards the rate of fluid breakdown. A significantly higher temperature permits the fluid to evaporate without remaining in intimate contact with the titanium. The older fluids (e.g., Skydrol 500B) do not contain inhibitors and are much more corrosive than the newer fluids like Hyjet IV.

SALT SPRAY TESTING

Table 7 shows the results of salt spray screening tests of coatings on aluminum panels. The monoaluminum phosphate and Kolene Kov Kote coatings were applied as aqueous solutions and did not readily form continuous films on bare aluminum surfaces; two cured coats were required for complete coverage. Good films were formed over Alodine 1200 conversion coated surfaces and, presumably, would be formed over a properly applied anodically or thermally oxidized aluminum surface.

Before curing, the monoaluminum phosphate coating dried as a glossy, transparent coating containing about 30% water as a gel. The gel dehydrated during curing, producing a porous white coating with a marked tendency toward chalking. The level of chromates in this coating provided a significant degree of corrosion protection during the 90-day salt spray exposure.

The Kolene Kov Kote air dried as a flat to semiglossy, transparent coating containing about 5% water. The cured coating remained hard and transparent with no tendency toward chalking, but had neither the thickness nor the corrosion inhibitors to adequately protect bare aluminum from corrosion.

Both the monoaluminum phosphate and the Kolene Kov Kote provided adequate corrosion protection when applied over the Alodine 1200 conversion coated aluminum.

WATER LEACHING

Table 8 shows the results of water leaching screening tests of the cured monoaluminum phosphate and Kolene Kov Kote coatings. The changes in pH can be related to several competing chemical reactions. The decreasing pH values indicated that the water was becoming acidified, partly by carbon dioxide diffusing through the thin polyethylene cover. A stronger source of acidity was chromic acid leached from the monoaluminum phosphate coating. The increasing pH values indicated that the water was becoming more alkaline, partly by aluminum reacting with the water. A much stronger source of alkalinity was potassium hydroxide leached from the Kolene Kov Kote coating.

The pH changes observed in these tests indicated that very little leaching occurred with any of the coatings. In the absence of a wetting agent, the chromates leached from the monoaluminum phosphate coating would not be sufficient to completely inhibit corrosion on the aluminum substrate. (Increased chromate and increased corrosion inhibition would be provided by the use of an Alodine 1200 conversion coating, as can be seen in table 7). The amount of hydroxide leached from the Kolene Kov Kote would

Table 7. — Salt Spray Testing of Aluminum Panels

Processing	Appearance after 30-day salt spray exposure
Alkaline clean and deoxidize only	Heavy general corrosion
One coat of monoaluminum phosphate plus 10-minute cure at 590 K (600°F)	Very light corrosion (16 pits)
Two coats of monoaluminum phosphate plus 10-minute cures at 590 K (600°F)	Traces of corrosion (5 pits)
Two coats of Kolene Kov Kote plus 10-minute cures at 590 K (600°F)	Moderate corrosion (80 pits)
Alodine 1200 (1-minute immersion)	Very light corrosion (13 pits)
Alodine 1200 plus two MAP coats with 10-minute cures at 590 K (600°F)	No corrosion
Alodine 1200 plus two Kov Kotes with 10-minute cures at 590 K (600°F)	No corrosion

Table 8. — pH After Immersion in Distilled Water

Immersion time, days	Distilled water (no specimens)	Monoaluminum phosphate		Monoaluminum phosphate plus wetting agent		Kolene Kov Kote	
		Titanium	Aluminum	Titanium	Aluminum	Titanium	Aluminum
0	6.92	6.92	6.92	6.92	6.92	6.92	6.92
4	6.80	5.85	6.20	6.05	6.15	9.30	9.10
5	6.50	5.75	5.75	5.75	6.00	8.05	8.30
7	6.50	5.65	5.50	5.60	5.75	7.70	8.10
19	6.50	5.45	5.15	5.25	5.45	7.65	7.95

not be sufficient to initiate corrosion of the aluminum (report FAA-SS-73-5-6 showed that a pH of about 11 was required to initiate corrosion) or even to maintain an appreciably alkaline solution in air containing carbon dioxide.

Carefully controlled leaching tests were not performed on the phosphate ester lubricant protection systems. The chemistry of these coatings indicates that the Hanovia Gold no. 6854 would form an all metal coating with no harmful, water-soluble constituents. The Andrew Brown B-2000 coating contains sodium and lithium silicates which would be subject to water leaching and would raise the pH until accelerated corrosion of the braze alloy would occur.

ACOUSTIC HONEYCOMB TESTS

The acoustic honeycomb sandwich specimens were unaffected by the thermal/phosphate ester fluid exposure. Visual examination showed no pitting, etching, or embrittlement to the aluminum braze metal, the titanium face sheets, or the titanium honeycomb core. Residual phosphate ester fluid and brown varnish-type fluid breakdown products were on most surfaces of the specimens. Fluid breakdown did not progress to the point of forming the heavy black deposits noted in the 96-hour dripping test. All of the coatings appeared to be intact.

Table 9 shows that all of the acoustic honeycomb sandwich specimens were corroded during the subsequent 120-day salt spray exposure. Salt spray corrosion progressed to the point that flatwise tensile tests could only be made on those specimens that had been protected with monoaluminum phosphate as a second coating. The flatwise tensile strength of the specimens coated with gold plus monoaluminum phosphate was reduced to less than 5%. The flatwise tensile strength of those (nongold) specimens protected with monoaluminum phosphate was reduced to an average of 60%. The degree of corrosion penetration of the honeycomb outer braze fillets during 120 days of salt spray exposure was in agreement with the findings of the previous program (report FAA-SS-73-5-6).

The corrosion damage to interior braze fillets was very much greater than that previously encountered with acoustic honeycomb. Table 10 shows that the previous investigation was accomplished using acoustic honeycomb specimens with the same size holes, but with the number of open holes after brazing reduced from the current 17 per cell to only one per cell. During prolonged salt spray exposure, specimens with only one open hole per cell had restricted solution circulation and a tendency for precipitated salts to block the hole, so that the corrosion rate for interior cells was much less than that for exterior cell braze fillets. The specimens with 17 holes per cell used during the present investigation allowed relatively free circulation of oxygen and corroding media in the interior cells, so that the interior and exterior braze fillets corroded at similar rates.

The 120-day salt spray exposure proved to be too severe for evaluating the relatively minor differences between corrosion protection coatings or for determining any acceleration in corrosion caused by the phosphate ester protection coatings. A 60-day salt spray exposure would be more appropriate for any further tests of coatings on

Table 9. — Salt Spray Exposure On Acoustic Honeycomb Sandwich Specimens^a

First coating	Second coating	Results of examination	FWT ^b strength ratio
None	None	Very severe corrosion	0
Andrew Brown B-2000	None	Very severe corrosion	0
Hanovia Gold No. 6854	None	Very severe corrosion	0
Hanovia Gold No. 6854	Kolene Kov Kote	Very severe corrosion	0
None	Kolene Kov Kote	Very severe corrosion	0
Hanovia Gold No. 6854	Monoaluminum phosphate	Severe corrosion	0.05
None	Monoaluminum phosphate	Moderate corrosion	0.60

^a120-days salt spray. Face sheet perforated with 1.3 mm (0.050 in.) holes, 35% open area.

^bRoom-temperature flatwise tensile strength ratio, average values: after exposure \div before exposure. Average FWT values for acoustic specimens before exposure: 8.62 MPa (1250 psi).

Table 10. — Effect of Geometry on the Number of Open Holes per Cell

	Hole diameter	Honeycomb core	Open area	Open holes per cell	
				Before brazing	After brazing
Previous investigation (report FAA-SS- 73-5-6)	1.3 mm (0.050 in.)	SC 4-20 NM	5%	1.6	1.1
Present investigation	1.3 mm (0.050 in.)	SC 6-20 NM	35%	25	17.5
Potential acoustic designs, similar holes	1.3 mm (0.050 in.)	SC 6-20 NM	8%	5.7	4.0
Potential acoustic designs, larger holes	1.5 mm (0.060 in.)	SC 6-20 NM	8%	4.0	2.8

acoustic honeycomb sandwich panels. The 120-day salt spray exposure is not a valid test for evaluating the corrosion resistance of acoustic ABTi structure for commercial airline service where the structures will be heated and shielded from direct contact with the weather.

The results of the salt spray tests provide a strong indication, however, that a corrosion protection finish is needed for ABTi acoustic honeycomb sandwich structure. Two coats of monoaluminum phosphate provided a reasonable degree of corrosion protection at a weight penalty of 0.1 kg/m^2 (0.02 lb/ft^2). Two coats of Kolene Kov Kote, weight penalty of only 0.02 kg/m^2 (0.005 lb/ft^2), did not provide appreciable corrosion protection to bare aluminum. A comparison of the results from tables 7 and 9 indicates that an Alodine 1200 pretreatment would have greatly improved the corrosion protection afforded by either the monoaluminum phosphate or the Kolene Kov Kote coatings. The controls for the Alodine 1200 solution, or other MIL-C-5541 colored coating solutions, would require adjustment to extend the immersion time from the present 1 to 3 minutes to the 10 to 30 minutes required for vacuum-ambient pressure cycling. The application of a heavy-duty phosphate ester fluid/corrosion protection system to an ABTi acoustic honeycomb sandwich assembly could be achieved by the following procedure:

1. Apply corrosion protective finish to the acoustic honeycomb assembly so as to ensure penetration of all interior cells.
 - a. Rack the assembly so that rotation or other part movement will orient the perforated face sheet up during solution immersion and down during drainage.
 - b. Subject the assembly to at least three vacuum/ambient pressure cycles during each immersion-processing step and to at least five vacuum/ambient pressure cycles during each rinsing step and the coating drainage step. An absolute pressure 5% of ambient pressure is a satisfactory vacuum.
 - c. Alkaline clean and rinse at room temperature if the interior cells have been exposed to oils, oily fumes, or cutting fluids other than distilled water or Freon TB-1. The Greater Mountain Chemical Co. GMC 528B or Wyandotte Aerowash cleaners diluted with four parts water are satisfactory.
 - d. Deoxidize and rinse if oxides or other contaminants on the braze fillets prevent formation of a proper chromate film in step (e). Wyandotte 2487 at 60 g/l (8 oz/gal), 30% nitric acid, or similar deoxidizers having an etch rate less than 0.003 mm per hour (0.0001 in/hr) on aluminum are satisfactory.
 - e. Apply Alodine 1200 or similar colored MIL-C-5541 conversion coatings. Adjust the solution composition so that a nonpowdery, colored coating will form in 10 to 30 minutes and will pass the MIL-C-5541 corrosion test.
 - f. Immersion apply the corrosion protection coating and drain. The monoaluminum phosphate solution contains, by weight, 26% $\text{Al}(\text{H}_2\text{PO}_4)_3$ + 3.7% MgNO_3 + 7.6% CrO_3 in water. The Kolene Kov Kote solution is used as received.

- g. Air or vacuum dry the coating as required to prevent blistering during curing.
 - h. Cure the coating. An overnight cure at 405 to 425 K (265° to 300° F) or a 10-minute cure at 590 K (600° F) is satisfactory.
 - i. Reapply and cure coating per steps (f) to (h).
2. Apply protective finish to surfaces that could be exposed to wetting by phosphate ester hydraulic fluid during elevated temperature service.
 - a. Abrade surfaces with Scotchbrite.
 - b. Spray apply a coating of Hanovia Liquid Bright Gold no. 6854.
 - c. Cure 10 to 15 minutes at 715 ± 14 K ($825^\circ \pm 25^\circ$ F).
 - d. Reapply and cure gold coating per steps 2(b) and (c).
3. Apply corrosion protection finish to exposed outer edges of honeycomb core.
 - a. Mask perforated face sheet and gold coated face sheet as required to prevent entrapment of abrasive particles or damage to the coatings.
 - b. Dry abrasive blast with fine (150 to 200 mesh) aluminum oxide at approximately 0.14 MPa (20 psig) pressure.
 - c. Spray apply two coats of protective finish and cure per the supplier's recommendation. Finch 454-4-1 epoxy primer is satisfactory for extended service at temperatures up to 420 K (300° F). DeSoto 763-003 silicone primer is satisfactory for extended service between 420 and 505 K (300° and 450° F). Sermetel W aluminum filled silicate coating is satisfactory for extended service between 505 and 755 K (450° and 900° F).
 - d. Cure the finish per the supplier's recommendation. The Sermetel W finish requires a 30-minute cure at 605 K (625° F) after each coat.
 - e. Glass bead peen the Sermetel W finish.

CONCLUSIONS

Extreme service evaluations show that aluminum-brazed titanium (ABTi) honeycomb sandwich is not subject to attack by most service chemicals and that coatings can be used to provide additional protection against the most severe environments.

The following specific conclusions were reached:

1. Both structural and acoustic ABTi are strengthened and corrosion resistance is increased by prolonged thermal exposure, particularly exposure in the range of 590 K (600° F).
2. Bare titanium is susceptible to hot salt pitting by seawater at temperatures of 700 K (800° F) and higher.
3. The ABTi system is not susceptible to stress corrosion, stress-accelerated corrosion, or liquid metal embrittlement due to pressure contact of titanium with silver-plated nuts at temperatures up to 755 K (900° F).
4. The ABTi system is not susceptible to attack by the fuels, engine oils, deicers, or cleaning materials that will be encountered in ambient or elevated temperature commercial airline service.
5. The titanium is subject to etching and hydrogen embrittlement when exposed to dripping phosphate ester hydraulic fluids at elevated temperature. Excellent resistance to this attack is provided by two coats of Hanovia Gold no. 6854.
6. Exposed aluminum braze fillets can become corroded during prolonged service in a marine environment and should be protected with a suitable corrosion-resistant finish.
7. Accelerated corrosion tests indicate some inherent environmental degradation might occur during long-term use. Identification of proper inspection techniques and/or corrosion protection may be required for some specific applications.
8. The corrosion resistance of ABTi honeycomb sandwich structure with nonperforated face sheets is totally adequate for commercial airline service. Satisfactory finishes have been developed to provide complete corrosion protection to exterior braze fillets under all anticipated commercial airline service conditions.
9. The inherent corrosion resistance of acoustic ABTi honeycomb sandwich with one or more perforated face sheets is satisfactory for commercial airline service where the structures will be frequently heated and shielded from direct contact with the weather.
10. Additional work is needed on finishes for interior braze fillets in acoustic honeycomb sandwich to permit service in an unsheltered environment.

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16. Abstract <p>This program continued the long-term flight service and jet engine exhaust tests initiated under the DOT/SST follow-on program. Additional tests were performed to evaluate degradation of ABTi structure during prolonged exposure to extreme environments: elevated temperature exposure to airline service fluids, hydraulic fluid, and seawater, followed by laboratory corrosion tests. Solid-face and perforated-face honeycomb sandwich panel specimens, stressed panel assemblies, and faying-surface brazed joints were tested.</p> <p>This report covers the results of the extreme service tests, phases II, III, and IV. The extended service evaluations, phase I, are still underway, and are not treated in this report.</p> <p>This investigation showed that the corrosion resistance of ABTi is satisfactory for commercial airline service. Unprotected ABTi proved inherently resistant to attack by all of the extreme service aircraft environments except: seawater at 700 K (800° F) and above, dripping phosphate ester hydraulic fluid at 505 K (450° F), and a marine environment at ambient temperature. The natural oxides and deposits present on titanium surfaces in airline service provide protection against hot salt corrosion pitting. Coatings are required to protect titanium against dripping phosphate ester fluid at elevated temperatures and to protect exposed acoustic honeycomb parts against corrosion in a marine environment.</p>			
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